Renewable and Sustainable Energy Reviews 29 (2014) 37–51

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Status and development of hybrid energy systems from hybrid ground source heat pump in China and other countries

Zishu Qi [a,b,c], Qing Gao [a,b,*], Yan Liu [a,b], Y.Y. Yan [d], Jeffrey D. Spitler [e]

[a] *State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130025, PR China*
[b] *Department of Thermal Energy Engineering, Jilin University, Changchun 130025, PR China*
[c] *School of Municipal and Environment Engineering, Jilin Architectural and Civil Engineering Institute, Changchun 130118, PR China*
[d] *University of Nottingham, Nottingham NG72RD, UK*
[e] *Oklahoma State University, StillWater, OK 74078, USA*

A R T I C L E I N F O

Article history:
Received 9 February 2011
Received in revised form
15 August 2013
Accepted 24 August 2013
Available online 14 September 2013

Keywords:
HGSHP
HES
Development
Task
Proposal

A B S T R A C T

Hybrid energy systems (HES) facilitate the efficient utilization of renewable resources and sustainable energy, and they are expected to be more prevalent in the future. With ground source heat pump (GSHP) as the main body and core technology, the hybrid ground source heat pump (HGSHP) system is used frequently in recent years and its integration and synthesis skills face higher requirements. The worldwide hybrid system has usually been composed of types of energy source devices, such as solar collector, boiler (coal, gas, oil), electric heater, waste energy device, cooling tower, cooler, and thermal storage system with natural cold and hot. Actually, they lead to the complicated unsteady processes and various hybrid energy systems. In China, the applications of these systems are growing year by year, but the new technology breakthrough is being in difficulty and even in an awkward situation. This paper review the progress of GSHP combined with HES all over the world, and surveyed the development of HGSHP in China. Meanwhile, the basic proposals for development in the future are presented to make up the gap in the field of HES and HGSHP. A coming work aims to research the basic problems during the demonstration application, such as investigation of system design parameters, component configuration and control strategies of a HGSHP system. These problems will strengthen theoretical and practical understanding of HES and facilitate more extensive application of HGSHP in China.

Contents

* Corresponding author at: Department of Thermal Energy Engineering, Jilin University, Changchun 130025, PR China. Fax: +86 431 8509 4241.
E-mail addresses: gaoqing@jlu.edu.cn, senior00685@163.com (Q. Gao).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.059

1. Introduction

Hybrid ground source heat pump (HGSHP) systems incorporate both ground source heat pump (GSHP) systems and auxiliary thermal rejecters (or supplemental thermal sources), such as cooling towers, fluid coolers, pavement heating systems, shallow ponds, waste heat, solar collectors and boilers [1]. GSHP systems have become increasingly common in residential, commercial, and institutional buildings. In cases where there is significant imbalance between the annual heat rejection to the ground and the annual heat extraction from the ground, the loop fluid temperature tends to rise (or fall) from year to year. This effect can be moderated by increasing the size of ground loop heat exchanger. However, the capital cost requirements may be excessive and an alternative is to add an additional thermal sink or source. Nowadays the HGSHP systems are becoming an attractive choice for air conditioning in buildings due to their advantages of high energy efficiency and environmental friendliness compared with the conventional alternatives.

Hybrid energy systems (HES) are strategic and necessary measures for the efficient utilization of renewable resources and sustainable energy. HES can substitute the fossil fuels by using stored heat (cold) energy or renewable energy. The hybrid system can use the fluctuating energy more efficiently by matching the energy supply with demand. By contributing to energy efficiency, it significantly reduces environmental impacts from energy activities, increases the potential uptake of some renewable energy technologies, amplifies the potential of sustainable energy development and subsequently leads to better energy security. As we know, the most important aspect of HES is combining with the progress of HGSHP in the field of using geothermal energy.

Direct-use of geothermal energy is one of the oldest, most versatile and a common form of utilization of geothermal energy [2]. In 2010, the total installed capacity for geothermal direct utilization was 50.6 GW in the world, indicating a 78.9% increase over that of 2005, and a compound annual growth rate of 12.33% [3]. The worldwide geothermal energy use was 438.1 PJ/y, indicating a 60.2% increase over that of 2005 and a compound annual growth rate of 9.89%. The worldwide capacity factor was 0.27 (this number reflects the equivalent percentage of full load operating hours per year), down from 0.31 in 2005 and 0.40 in 2000. GSHP had the largest installed capacity and energy use, accounting for 69.7% and 49.0% of the worldwide capacity and energy use, respectively. The installed capacity was 35.2 GW and the energy use was 214.8 PJ/y. Energy savings amounted to 46.2 million tons of equivalent oil annually, preventing 46.6 million tons of carbon and 148.2 million tons of CO_2 being released to the atmosphere which includes savings in GSHP system. Assuming that these growth rates have persisted in the last 2 years, global geothermal heat capacity reached an estimated 66 GW in 2012, delivering as much as 548 PJ/y of geothermal energy use [4].GSHP represents the largest and historically fastest-growing segment of geothermal direct use. In 2012, it reached an estimated 50 GW of capacity; this amounts to about three-quarters of estimated total geothermal heat capacity, and more than half of heat output (> 300 PJ/y).

Most of the installations occur in North American, Europe and China, increasing from 26 countries in 2000 to 33 countries in 2005, 43 countries in 2010 and at least 78 countries in 2012. China remains the presumptive leader in direct geothermal energy use (75.3 PJ/y in 2010), followed by the United States (67.7 PJ/y in 2012), Sweden (49.7 PJ/y in 2010), Turkey (36.7 PJ/y in 2010), Iceland (25.9 PJ/y in 2012), and Japan (25.6 PJ/y in 2010). Iceland, Sweden, Norway, New Zealand, and Denmark lead for average annual geothermal energy use per person. About 90% of Iceland's total heating demand is derived from geothermal resources. In the EU, GSHP capacity rose by about 10% between 2010 and 2011, to a total of 14 GW, led by Sweden (4.3 GW), Germany (3 GW), France (1.8 GW), and Finland (1.4 GW). Canada had more than 100,000 systems in operation by early 2013, and the United States is adding about 50,000 heat pumps per year. In 2012, Ball State University in Indiana installed the largest U.S. ground-source closed-loop district geothermal system to heat and cool 47 buildings [5]. In China, geothermal district heating capacity has continued to increase at about 10% annually. The total installed capacity was 8.9 GW and the energy use was 75.3 PJ/y in 2010.

The number of policies and targets in place worldwide to support the development and deployment of renewable energy technologies increased yet again in 2012 and early 2013, and the number of countries supporting renewable energy continued to rise. As of early 2013, renewable energy support policies were identified in 127 countries, an increase of 18 from the 109 countries reported in 2012. More than two-thirds of these countries were developing or emerging economies. Besides, countries continued to enact new policies and targets for the promotion of renewable technologies in the heating and cooling sectors during 2012. Roughly 20 countries have specific renewable heating/cooling targets in place, including those for solar water heating. In addition, at least 19 countries/states have heat obligations/mandates to promote the use of renewable heat technologies [4]. Fig. 1 presents estimated renewable energy share of global final energy consumption in 2012.

China is one of the most populous countries and has been the largest energy consumer in 2013. Rising energy demand and import has made China a significant factor in the world energy market. Taking into account the characteristics of energy supply, China is facing two severe challenges of energy shortage and environment protection. Therefore, in order to maintain fast and stable economy, China has to find several policy measures for energy development and consumption [6].

In 2011, China non-fossil energy accounted for 8% of the total primary energy consumption, which means an annual reduction of more than 600 million tons of CO_2 emission. Through unswerving

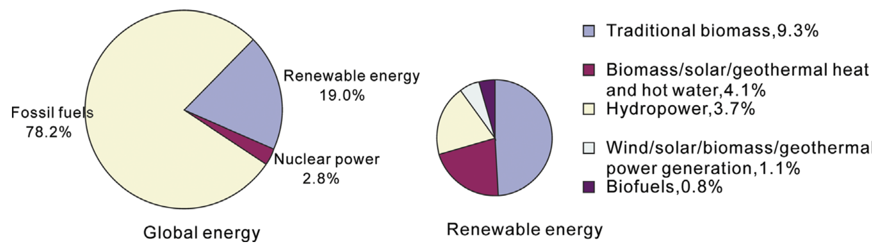

Fig. 1. Renewable energy share of global final energy consumption (2012).

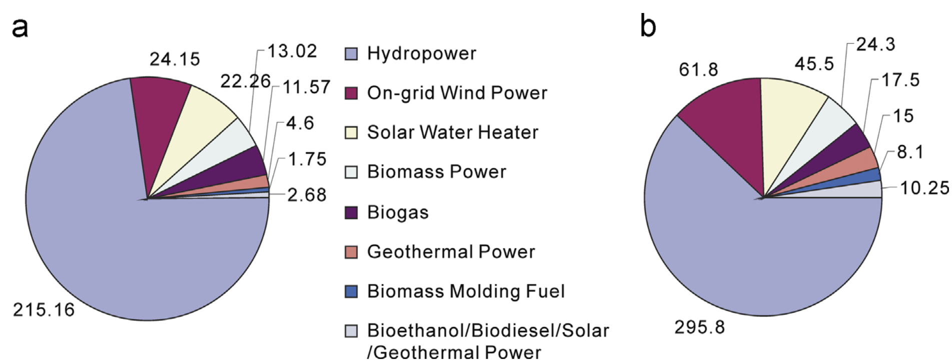

Fig. 2. China renewable energy production in 2011 (a) and renewable energy targets by 2015 (b) (million TCE).

efforts in developing new and renewable energy sources, China endeavors to increase the shares of non-fossil fuels in primary energy consumption and installed generating capacity to 11.4% and 30%, respectively, by the end of the 12th Five-Year Plan (2010–2015) [7]. By 2015, the annual renewable energy consumption will reach 478 million tons of standard coal equivalents (TCE), including 400 million TCE coming from commercialized renewable energy [8]. Fig. 2 presents China renewable energy production in 2011 and renewable energy targets by 2015.

Obviously, if a type of efficient utilization of renewable energy can be combined with the thermal energy storage for the use of HGSHP and it will be a green way of building energy.

2. Basic type of HGSHP

GSHP systems that incorporate a supplemental heat source or sink have been referred to as “HGSHP systems”. Auxiliary heat rejection can be accomplished with a cooling tower, fluid cooler, pond, or pavement heating system. Supplemental heat sources could be solar collectors, boilers, waste heat and so on.

In 1997, American scholars Kavanaugh and Rafferty developed a design procedure to size the ground loop heat exchanger and the supplemental heat source or sink [9]. For the cooling dominated building, the ground loop heat exchanger of the HGSHP system is then sized to meet the heating loads of the system, balanced by a reduced portion of the cooling loads. For the heating dominated building, the ground loop heat exchanger of the HGSHP system is then sized to meet the cooling loads of the system, balanced by a reduced portion of the heating loads [10]. The required ground loop heat exchanger is then much smaller compared to the one that would meet all of the heating and cooling loads.

2.1. From GSHP to HES

GSHP systems utilize the earth, ground water, or surface water as a thermal source/sink for providing heating and cooling. The system is one of the fastest growing applications of renewable energy in the world with annual increase 10% over the past decade [11]. GSHP systems are receiving increasing interest because of their potential to decrease primary energy consumption and thus reduce emissions of greenhouse gases.

HES integrated with multiple energies (e.g. geothermal energy, solar energy, waste heat, fuels, electricity and ambient air), energy storage buffer and heat pump can not only reduce the time mismatch between the supply and the demand of energy resources, but also enable the use of natural ambient energy. HES facilitate the efficient utilization of renewable energy, and are expected to be more prevalent in the future.

Additional heat sinks or sources can compensate a temporary or long imbalance between cooling loads and heating loads or alleviate it greatly. Perhaps in the present, it becomes the most frequently used hybrid energy technology in North America and Europe. In the past 15 years, many more applications of HES have been studied and implemented. Now, there are two common applications types of HES: cooling tower supplemented ground source heat pump (CTGSHP) and solar assisted ground source heat pump (SAGSHP) system. The former is fit for cooling dominated building, and the latter is fit for heating dominated building. Both types of hybrid systems offer smaller size of heat exchanger and much lower first cost than those of original systems. With the obvious environmental benefits, HES will play an important role for the cleaner future.

2.2. HGSHP with solar collection

Solar thermal technologies contribute significantly to hot water production in many countries and increasingly to space heating and cooling as well as industrial processes in the world. In 2010, China had 170 million m^2 of solar heating and a policy target of 300 million m^2 by 2020 [12].

During the last decade, a number of investigations have been conducted by some researchers in the design, modeling and testing of solar assisted heat pump (SAHP) systems [13]. These studies can be categorized into four groups as follows: (i) SAHP for water heating [14,15], (ii) SAHP with energy storage for space heating [16], (iii) SAHP with direct expansion for space heating [17,18], and (iv) SAGSHP heating system.

As one form of HGSHP systems, SAGSHP system is used frequently in the world. The SAGSHP systems are economically attractive in the cold areas. Generally speaking, the ground heat exchanger is sized to meet the cooling load and the supplemental heat device is sized to meet the excess heating load that is unmet by the ground heat exchanger.

The concept of a combination of a solar collector and buried pipes to permit storage of solar energy in the ground was first proposed by American scholar Penrod in 1956. In 1982, a horizontal heat pump system coupled with low temperature solar collectors was tested in Austria. The use of an SAGSHP system in Tianjin, China, was studied in 1995 [19,20]. Recently, a number of efforts have been made to investigate the performance and applications of the SAGSHP systems. In 2004, an SAGSHP system was built and operated by Trillat-Berdal et al. in France [21]. The system was designed to provide domestic hot water, space heating and cooling. Experimental results indicated an average COP (coefficient of performance) of 3.75 in heating mode.

An SAGSHP system was installed at Solar Energy Institute of Ege University, Turkey [13]. During the experimental period, the COP_{HP} varied from 2.00 to 3.125, while the system COP was approximately 5–20% lower than COP_{HP}. The experimental results also showed that the single heating operation could not meet overall heat loss of building if ambient temperature was very low. The hybrid operation mode could be suggested as a good solution in the Mediterranean and Aegean regions of Turkey, if a peak heat load could be easily controlled.

Modeling and calculating for simulation are important tools in design and prediction for SAGSHP systems [22]. American scholar Chiasson et al. discussed the viability of using a solar collector, as a supplemental heat source for a GSHP system [23,24]. The study used loads obtained by simulation of a heating dominated 4924 m^2 school building in six U.S. cities in cold climates. The seasonal thermal solar energy storage in the ground was found to be enough to offset a larger ground storage volume that would be required with a conventional GSHP system. The use of a supplemental solar collector system results in a reduction in ground loop heat exchanger size by 34%. A simple payback analysis shows that the proposed system will pay back the initial cost in less than 10 years. Certainly, supplemental heat source increases the first cost. In general, negative side effects, if any, are negligible to some extent compared to the original systems.

In 2013, a study demonstrates that HGSHP system combined with solar thermal collectors is a feasible choice for space conditioning for heating dominated houses in Milton, Canada. It was shown that the solar thermal energy storage in the ground could reduce 15% of ground heat exchanger length. Sensitivity analysis was carried out for different cities of Canada and the result showed that Vancouver, with mildest climate compared to other cities, was the best candidate for the proposed SAGSHP system with a ground heat exchanger length reduction to solar collector area ratio of 7.64 m/m^2. The SAGSHP system performance in different cities in Canada is shown in Table 1.The net present value of the proposed hybrid system based on the 20-year life-cycle cost analysis was estimated to be in a range of 3.7–7.6% lower than that of the GSHP system [25].

2.3. Other HGSHP

2.3.1. Waste heat

Heat pumps can use waste heat sources such as industrial process, cooling equipment or ventilation air extracted from buildings. Over the last 2 decades, the sewage source heat pump has gradually come into use. Many researchers have carried out some investigations about urban sewage heat pump systems [26]. In Japan, a simulation study of district cooling/heating system using sewage water as an energy source shows that, compared with conventional air source heat pumps, wastewater source heat pumps could help reduce energy consumption by 34%, lower the emission of CO_2 by 68% and control the generation of NO_x by 75% [27]. This type of heat pump systems is widespread in Asian countries. The sewage heat pump system was designed and analyzed in Korea [28]. This study was performed to investigate the feasibility of the wastewater use for heat pump as a heat source and to obtain engineering data for system design. As a result, it is forecasted that the yearly mean COP of heat pump is about 4.8 and heat pump can supply 100% of hot water load except weekends of winter season. Therefore, this system using wastewater from sauna, public bath, building, etc. can be effectively applied not only to water heating but also space heating and cooling in regions like as Korea.

Besides, hot water energy accounts for 14% of residential energy consumption. Estimates by the U.S. Department of Energy (DOE) indicate that the equivalent of 235 billion kWh of hot water is discarded annually through drains, and 25–30% of this energy is in fact recoverable by a Gravity Film Heat Exchange (GFX) [29]. The GFX is a simple heat exchanger design for heat recovery that arises from a grant under the DOE Inventions Program. This straightforward design is a vertical, counterflow heat exchanger that extracts heat out of drain water (usually warm) and applies this heat to preheat the cold water entering the building. The GFX is a simple

Table 1
The SAGSHP system performance in different cities in Canada.

City (annual heating to cooling load ratio)	Solar collector	Ground loop heat exchanger		Annual system energy		Reduced GLHE (m); length/collector area (m/m^2)
	Area (m^2)	Total length (m)	Borehole (m)	Heating (MJ)	Cooling, MJ	
Vancouver (1.54)	0 6.81	220 168	4 × 55 4 × 42	46,305 46,119	5364 5623	52;7.64
Toronto (2.33)	0 6.81	220 180	4 × 55 4 × 45	44,793 44,749	6434 6631	40;5.9
Montreal (2.43)	0 6.81	220 184	4 × 55 4 × 46	46,766 46,779	6989 7174	36;5.28
Ottawa (2.71)	0 6.81	220 188	4 × 55 4 × 47	46,327 46,445	6150 6331	32;4.7
Halifax (3.35)	0 6.81	220 196	4 × 55 4 × 49	49,566 49,301	5015 5268	24;3.52
Edmonton (3.80)	0 6.81	220 200	4 × 55 4 × 50	51,979 52,052	5935 6076	20;2.93

and effective method for significantly reducing the energy needed to produce hot water.

A recent field evaluation of the GFX conducted by the U.S. Pennsylvania Power and Light found the simple payback of a residential GFX system ranging from 2 to 5 years. This was based on an installed GFX cost of $500 and electricity savings ranging from 800 kW h/y to 2300 kW h/y depending on the average number of daily showers in each home. The economics of the GFX is improved with the number of daily showers in the residence as expected [29]. To evaluate the performance of the GFX in a multifamily setting, Oak Ridge National Laboratory through DOE's Appliance and Emerging Technology Program identified a site for the study, installed a GFX along with instrumentation into this site and initiated a 1-year study. The GFX saved a total of 2800 kWh of electricity over the period. If this electricity were valued at $0.08/kWh, the savings in operating costs would be $225 [30].

2.3.2. Boiler

In the cold districts, the HGSHP system may consist of a closed-loop design incorporating an additional boiler, which can maintain the temperature above 0 °C in vulnerable parts of the system to avoid frost damage and enable a better performance. The boiler is assumed to be infinitely adjustable with no degradation due to part-load effects, and maintains the minimum set point temperature at all times of the year.

In Europe, most heat pump units are sized for the heating load and are often designed to provide the base load with peaking by fossil fuel. Applications of the GSHP system incorporating an additional boiler in project started in Canada to fit into the space limitations of the site [31]. Besides, in order to be operational all year round, the system had to use a propylene ethanol solution and installed a gas-fired boil to withstand continental climate conditions. Although this system is more expensive than a conventional one, it results in annual natural gas savings of 96%. Electricity consumption is slightly higher, 552 MW h compared with 528 MW h for a conventional system. Due to this massive reduction in natural gas consumption, CO_2 emissions have dropped to almost 90 t/y.

2.3.3. Cooling tower

Supplemental heat rejection can be accomplished with a fluid cooler, cooling pond, or pavement heating system and so on. Perhaps the most obvious candidate for a supplemental heat rejecter in a hybrid system would be a conventional open-circuit cooling tower. For a HGSHP system, the boreholes can be sized based on the heating loads. The boreholes in conjunction with a supplemental heat rejecter would allow the system to meet the cooling loads. The main advantage of this system is that it more closely balances the heat rejected and extracted for the borehole heat exchangers over the course of a year. Another added benefit is the possible decrease in first cost and operating cost compared to a conventional GSHP system [32].

A larger-scale application of CTGSHP system is in USA, such as a military base administration building in Louisiana, the Paragon Center building located in Pennsylvania, and an elementary school building in New Jersey. Until now, many researchers have tried to develop simulation models for a combined system with cooling tower. In the United States, Oklahoma State University researchers [33] have investigated the advantages and disadvantages of various control strategies for the operation of a GSHP system with a cooling tower under different climatic conditions. Man et al. [34,35] of the Hong Kong Polytechnic University reported a practical simulation model of the CTGSHP system by analyzing and modeling the heat transfer process of its main components on an hour-by-hour basis in China. A comparison was made among the impacts of four different control strategies on performances of two different HGSHP systems designed for a sample cooling dominated building, and an analysis of system investment considering the initial and operating cost was conducted based on the hourly calculation results.

Park et al. of the Korea University Honghee studied a HGSHP with a parallel configuration was optimized in the cooling mode by varying the refrigerant charge amount of the primary refrigerant loop, the secondary fluid flow rate of the ground loop and the supplemental loop in the HGSHP mode for the standard and the degraded ground thermal condition. The COP of the HGSHP with the parallel configuration was 21% higher than that of the conventional GSHP, and the heat rejection rate of the ground flow loop was 42% lower than that of the GSHP at the entering fluid temperature (EFT) of 40 °C in the ground heat exchanger and the EFT of 28 °C in the supplemental heat exchanger [36]. In addition, a performance comparison between the GSHP and the HGSHP with parallel and serial configurations was conducted by varying the exiting fluid temperature (ExFT), the fluid flow rate, the mean outdoor temperature, and the switching temperature of the hybrid operation. At the ExFT of 40 °C, the COP for the HGSHP with the parallel and serial configurations were 18% and 6% higher than that of the GSHP, respectively. The cooling seasonal performance factors of the HGSHP with the parallel and the serial configurations were 6.5% and 2.0% higher, respectively, than that of the GSHP for Daegu city in South Korea [37].

In Iran, a thermodynamic model based on energy and exergy analyses is presented, and an economic model of the CTGSHP system is developed according to the total revenue requirement (TRR) method. The proposed HGSHP system, including 12 decision variables, is considered for optimization. In the case of multi-objective optimization, an example of a decision-making process for selection of the final solution from the Pareto optimal frontier is presented. The results obtained using the various optimization approaches are compared [38].

2.3.4. Air source

Air source heat pump (ASHP) system is recommended for mild and moderate climate regions, where the winter temperature usually remains above −1 °C. The performance of an ASHP in heating mode decreases with the drop of air temperature outside. In order to more efficiently use heat pump systems, it is necessary to develop a system which utilizes both ground and air according to temperature conditions and building loads. Furthermore, during intermediate seasons (such as spring and autumn) with reduced heating and cooling loads, GSHP system is usually less efficient than ASHP system according to temperature conditions.

In Spain, N. Pardo et al. [39] simulated an office building in a cooling dominated area in order to evaluate the total electrical consumption of each configuration and obtain some results which could satisfy the thermal demand more efficiently. This research developed a hybrid heat pump system using dual ground and air heat sources. The results showed that the electrical energy consumption when the system employed a suitable configuration was around 60% compared with an ASHP system and around 82% compared with a GSHP system. It is reported that in Japan, the annual performance of the developed hybrid system improved by 2–7% compared with water cooling system, and by 4–18% compared with air cooling system. In the future, the optimal operation method switching between air and water cooling can be considered by Genetic Algorisms (GA) [40].

3. Overseas status in HGSHP

3.1. Overview

For the EU, national renewable energy plans collectively imply about 20% of heating by 2020. Germany's Renewable Energies

Heating Law, effective in 2009, requires all new residential buildings to obtain at least 20% of household heating and hot water energy from renewable energy, with an overall goal of 14% of total heating energy to come from renewable energy by 2020, including district heating systems. Other targets for share of heating (and cooling) from renewable energy by 2020 by EU members include Belgium (12%), Denmark (40%), France (33%), Greece (20%), Lithuania (39%), Romania (22%), Spain (19%), and the United Kingdom (12%). Very few countries outside of Europe have policy targets for shares of heating from renewable energy [12].

HGSHP as one form of GSHP systems, is widely used in Europe and North America, and expected to be more and more prevalent in the future. Literatures [41,42], respectively made a summary and survey for the current status and situation of HGSHP. HGSHP applications have slowly gained acceptance in the world energy market. Two HGSHP systems are prevalently implemented: SAGSHP and CTGSHP systems.

In HGSHP systems, the size of ground heat exchanger is reduced and auxiliary heat rejecters (or supplemental heat sources) are used to handle the excess cooling (or heat) loads during building operation. The size of ground heat exchanger in a hybrid system will vary with location and climate. But it must be at least large enough to handle the building base heating (or cooling) requirements. Hybrid systems can also be used for sites where the geological conditions or the available ground surface is not large enough to allow a ground heat exchanger for the building peak loads to be installed [43].

In fact, the climate in the northeast of China is similar to that of Sweden, so we can take their demonstrations as a reference example. As we know, in solving the issue of imbalance of heating/cooling load, now Europe and America have become representatives of the practical HGSHP systems utilization, and these countries have done a lot of research and development (R&D) work. In many countries, namely Sweden, Switzerland, Austria, Denmark, Norway, Poland, Turkey, Germany, France, USA, Canada, Japan and China, there are a large number of GSHP systems in operation which will facilitate the utilization of HGSHP.

Especially, American Brookhaven National Laboratory, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Oklahoma State University and Alabama University, Turkey Ege University and Karadeniz Technical University, Canada Ryerson University, Korea University, Germany Justus Liebig University, Poland Warsaw University of Technology and Cracow University of Technology, Japan Tokyo University and other overseas organizations performed researches on system configuration, and simulation calculation of model, design procedure and control strategy, and thus made it possible to increase the system performance and minimize system life-cycle cost. Their work has put a good platform for using HGSHP.

3.2. *Typical implementing demonstrations*

It is reported that in America, a 2230 m^2 military base administration building uses a HGSHP system in Fort Polk, Louisiana [33,44]. The system uses 70 vertical closed-loop boreholes, each 61 m deep with 3.3 m spacing. The observed data show that, over the period of 22 months monitoring, the amount of heat rejected to the ground is about 43 times higher than the amount of heat extracted from it. This is indicative of a very heavily cooling-dominated building. The supplemental heat rejecter is a 275 kW cooling tower and is controlled by a differential controller that activates the cooling tower fans when the heat pump exiting fluid temperature reaches 36 °C and deactivates it when the temperature falls below 35 °C. The relative energy consumption of the major system components over the study period is provided where the heat pumps account for 77% of the total energy consumption, the circulating pumps for 19%, the cooling tower fan for 3%, and the cooling tower pump for 1%.

It explores first cost savings that resulted from using a HGSHP design on the Paragon Center building located in Allentown, Pennsylvania, and an elementary school building in West Atlantic City, New Jersey [45]. The Paragon Center illustrates the need for a hybrid application as a direct result of geological conditions at the site where boreholes that were drilled deeper than 33.5 m collapsed due to high groundwater flow in limestone strata. The building area is 7436 m^2. The hybrid system consists of 88 boreholes, each approximately 38 m deep, and a closed-circuit fluid cooler of 422 kW maximum capacity. The elementary school expansion building in West Atlantic City is an example of a hybrid system where the available space for the borehole field was not sufficient to accommodate the number of boreholes required to fully meet the building's cooling loads. The building area is approximately 5856 m^2. A closed-circuit fluid cooler of 411 kW capacity is used, decreasing the required number of boreholes by more than 25% to 66 bores, each about 122 m deep. In both of the examples, a significant first-cost savings system is achieved, though with slightly higher operating and maintenance costs.

In Sweden, the long-term objective of seasonal storage is to store solar heat from the summer to the winter for space heating [46]. A residential area, Anneberg, with 50 residential new houses, is constructed in Danderyd, the north part of Stockholm. The city encourages the utilization of renewable energy. This solar heat application is one of the 10 largest solar heating plants in Europe and the very first with borehole storage in rocks. The systems have been in operation since spring 2002. Roof integrates 2400 m^2 solar collectors and the store covers 70–80% of the yearly heating and domestic hot water demand. During the summer, part of the collected heat is stored in a borehole store with 100 boreholes drilled in bedrock to 65 m depth. Groundwater-filled boreholes are fitted with double U-tubes as ground heat exchangers. The system includes low-temperature space floor heating and individual electrical heaters for peak and supplementary heating.

In addition, a Swedish manufacturer proposed a HGSHP system that uses heat recuperated from exhaust [47]. The system supplies heat continuously to the ground heat exchanger thereby reducing the peak load and the required borehole length in Sweden. They recommend using a compact collector composed of a series of closely-packed plastic pipes that are approximately 2 m high. With this system, the collector can be installed in a trench about 1 m below ground. Thus, expansive borehole drilling is avoided. However, the collector does not benefit from higher and more constant deep ground temperatures.

Researchers at the University of Savoy in France investigate the availability of a combined GSHP–thermal solar collector system [48]. They confirm the viability of these hybrid systems in meeting the heating and hot water requirements of single residence, while assuring a satisfactory level of comfort. After 11 months in operation, the solar heat injected into the ground represented 34% of the heat extracted from it by the GSHP. It proved that in case of no underground flow, the ground loads can be balanced by recharging the ground with solar heat for heating dominated buildings.

A large scale of energy conservation with SAGSHP system for greenhouse heating with a 50 m vertical 32 mm nominal diameter U-bend ground heat-exchanger has been implemented [49]. This system was designed and installed in Izmir, Turkey. In the heating mode, the heat extraction rate from the soil is found to be, on average, 57.78 W/m of bore depth. The entering water temperature to the unit ranges from 8.2 to 16.2 °C, with an average value of 14 °C. The COP of the heat pump is about 2.00 at the end of a cloudy day, while it is about 3.13 at the end of sunny day and fluctuates between these values at other times. The average

clearness index during operating period is computed as 0.56. The results show that HGSHP system can be suggested as the best solution in the regions of Turkey.

3.3. Relevant theoretical works

Since the 1990s, a great number of investigations were conducted by many researchers of the world in the design, modeling and testing of HGSHP and HES. Case studies, handbooks and standards are available for the installation procedures of HGSHP systems [50].

In fact, in the investigation of HGSHP and HES, experiments always coexist with the numerical calculation. Modeling and calculating for simulation are important tools in design and prediction. In the world, researchers have taken many simulations on HGSHP and HES and their works promote the development, such as simulating the performance of a pavement heating system with closed-loop GSHP system [51], visual modeling of the operation process in HGSHP system [52], modeling of individual components for HGSHP system [1], optimal sizing of HGSHP system [53] and so on. As we know, it is a very difficult task; so numerical analysis has been regarded as an effective way to simulate complex experiments and to save time and capital. Numerical experiments can also extend the limitation of experiments and predict and design the system at any working condition. In the present study, in parallel with the experimental test, improving the COP, reducing the initial capital investment and operation cost of HGSHP are studied by using HVACSIM+, MATLAB, TRNSYS and other software.

In America, Energy Center of Wisconsin Scott Hackel et al. monitored and analyzed three buildings employing HGSHP systems (two cooling-dominated, one heating-dominated) to demonstrate the performance of the hybrid approach [54]. Three demonstrations are summarized in Table 2. The buildings were monitored for a year and the measured data was used to validate models of each system. Additionally, they used the models to analyze further improvements to the hybrid approach and established that it has positive impacts, both economically and environmentally. Researchers hope that these lessons and tools can be used to get building owners/developers, who might reject a ground-source system due to high cost, to consider a less expensive HGSHP system instead of choosing conventional HVAC.

In a study [55], a rigorous mathematical, computational approach to size the GSHP within a hybrid system is presented by Canadian scholars. The methodology is tested for 10 cases from residential to commercial and industrial buildings in Canada. Using this methodology can result in significant reductions in initial costs of installation, payback period, and operation costs, when compared to following rules of thumb or using non-hybrid systems. In most cases, when optimization is performed, the GSHP meets a very large portion of the total annual heating and cooling demand of a building (usually greater than 80%).

Besides, some countries begin to focus on component configuration, the size of ground heat exchanger and auxiliary heat rejecters (or supplemental heat sources), climatic consideration and operating and control strategies for the HGSHP system. The most typical control strategies published include set point temperature, temperature difference and preset schedule control. A lot of issues will affect the choice of control strategies such as building location, building type, HGSHP system design, component characteristics, etc. For a wide range of cases, with different control strategies, set points, and the sizes of auxiliary heat rejecters, operating costs varied by up to 15% [10].

4. Domestic development status and relevant work of HGSHP in China

4.1. Brief review of HGSHP

In 1980s, some research institutions started research on GSHP in China. Since 1990, some scholars and engineers visited America, Sweden, Germany, Canada, etc. to study the technology of GSHP and HGSHP. In China, the first project of air and water multiple thermal sources heat pump system was installed in the Gezhouba hydropower plant in Yichang, Hubei province, in 1991. Presently, building area using the ground source heat pump technology in China has exceeded 0.14 billion m^2; yearly sales of ground source heat pump systems in China have exceeded 5 billion RMB and are growing at a speed above 30%; area using the single ground source heat pump system is up to 800,000 m^2 [56]. By the end of 2015, China is expected to complete the ground source heat pump heating (cooling) for an area of about 0.58 billion m^2 [8], when the total of geothermal energy development and utilization will be at least 70 billion RMB. HGSHP systems account for a considerable proportion in the market. Furthermore, these HGSHP engineering projects contain various categories, such as office building, hotel, residential building, workshop building, school, villa house, and hospital.

The governments at all levels in China have provided financial support to the technological and industrial development of geothermal energy. Interim Measures for Management of Special Fund for Applications of Renewable Energy in Buildings co-released by the Ministry of Construction and the Ministry of Finance lists the ground source heat pump as a key field to be supported, with financial assistance provided to projects meeting relevant conditions. According to a preliminary estimate, the governments at all levels in China accumulatively provided several billion RMB of financial subsidy for the development of geothermal energy, which has greatly promoted the technological development as well as exploitation and utilization of geothermal energy resources. The Chinese government will continue to offer

Table 2
Three demonstrations are summarized in study.

Full name	Cashman Equipment	East Career and Technical Academy	Tobacco Lofts at Findorff Yards
Location	Henderson, NV	Las Vegas, NV	Madison, WI
Area with GSHP system	19,050 m^2	23,320 m^2	5310 m^2
Ground heat exchanger size	360 bores, 122 m deep	420 bores, 122 m deep	39 bores, 85 m deep
Actual/Optimized	43,900 m/26,200 m	51,200 m/28,000 m	3320 m/2260 m
Supplemental device	2 × 879 kW cooling towers	2 × 587 kW cooling towers	58 kW boiler
Actual/Optimized	1758 kW/1510 kW	1174 kW/1410 kW	58 kW/88 kW
Savings for optimized equipment	$37/$m^2$	$37/$m^2$	$10/$m^2$
Pumping portion of HGSHP system energy	7%	12%	21%
Reduction in Carbon emission(GSHP/HGSHP)	46%/47%	19%/20%	11%/14%
Invest in HGSHP instead of conventional	10%	12%	9%
Invest in GSHP instead of HGSHP	5%	4%	1%

constant support for the exploitation and utilization of geothermal in the next several years.

The coexistence of various kinds of GSHP is caused by the different climate zones and the special nature resource of location, such as ground water HP (GWHP), ground-coupled HP (GCHP) and surface water HP (SWHP). Accordingly, we should make use of renewable energy in buildings based on different location and climatic zones. From a questionnaire of 231 national demonstration projects, type, quantity, area and percentage are shown in Table 3, which indicates that HGSHP area accounts for 27.5% in total. Fig. 3 shows quantity percentage of renewable energy demonstration projects. Table 4 shows the typical HGSHP projects in China.

There has been increasing number of patent applications related to GSHP over the past 2 decades in China. By early 2013, patent applications related to GSHP were more than 1600 [57]. Fig. 4 shows the number of the patent application from 1985 to 2013 [57,58]. As is shown, the patent applications are in the rapid development phase from 1999 to 2003. Since 2003, the number of patent applications has slowed down, which indicates that the GSHP is in maturity stage in China.

Among all the patents of GSHP, almost 60% of the patents are related to HGSHP system; especially SAGSHP accounts for a considerable proportion in total. As the applications of SWHP and GWHP are restricted by environmental policy, water source, and recharge technology, the related number of patents is decreased in recent years. Meanwhile, the number of the patents related to the GCHP is increased. These patents are used for air-conditioning, hot water, heating and others in China.

Table 3
A detailed list of renewable energy demonstration projects.

Type	Quantity	Area (T m^2)	Areas percentage (%)
GCHP	44	292.97	11.66
GWHP	73	841.28	33.49
SWHP	12	126.64	5.04
Seawater source HP	12	193.95	7.72
Sewage source HP	17	365.41	14.55
HGSHP:SAGSHP	62	513.62	20.45
HGSHP:GWHP+sewage source HP	7	90.06	3.59
HGSHP:GCHP+GWHP	1	13.7	0.55
HGSHP:seawater source HP+Sewage source HP	1	15	0.60
HGSHP:GCHP+sewage source HP	2	59.2	2.36
Total	231	2511.86	100

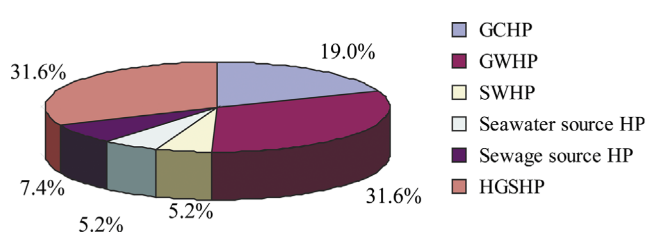

Fig. 3. Quantity percentage of renewable energy demonstration projects (2013).

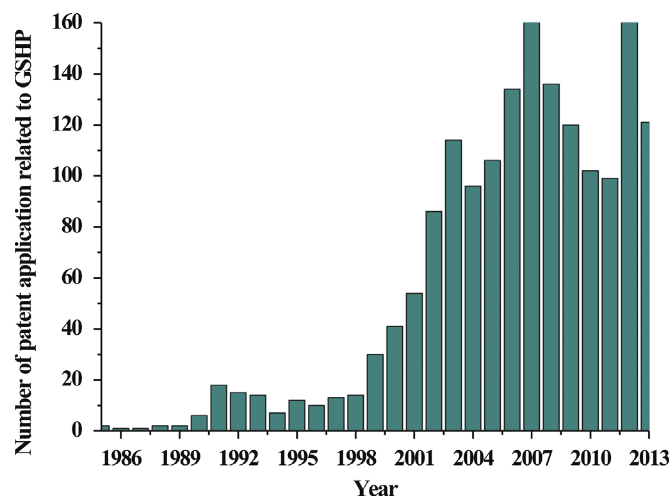

Fig. 4. The number of patent applications related to GSHP in China (2013).

Table 4
Typical HGSHP projects in China.

Location	Province	Type	Floor area (m^2)	Cooling load (kW)	Heating load (kW)	Investment cost (million RMB)	Annual operating cost (RMB/m^2)
Guangxi university student apartments	Guangxi	SAGSHP	10,080	hot water(1321 m^3/y)			5.76 RMB/m^3
Beijing Jianyan science and technology park	Beijing	Winter SAGSHP Summer SAGSHP	9460	195	408		
Beijing Jiuhua resort	Beijing	Winter GCHP steam heating Summer GCHP ice storage	131,262	13,000	10,500		
Beijing Yongyou software center	Beijing	Winter GCHP boil Summer GCHP ice storage	400,000	15,784	13,391	42	32
Beijing fruit market	Beijing	Winter GWHP Summer GWHP ice storage	52,161	8200	4000	14	40.6
Liaoning Armed Police Command Center	Liaoning	winter GCHP boil summer GCHP	59,920	4957	4910		29.37
Xi'an “Gate of the city”	Shanxi	Winter GCHP steam heating Summer GCHP cooling tower water chiller	101,161	8582	5700	26	24.6
Office building of Ningbo Jiale enterprise	Zhejiang	Winter GCHP Summer GCHP cooling tower	11,000	960	580		27.77
Office building of Ningbo Yinzhou Municipal State Taxation Bureau	Zhejiang	Winter GCHP Summer GCHP cooling pond	19,000	2400	1600	9.6	36

4.2. Relative state law and policies

Knowing that policies are a prerequisite to support scaled application of geothermal energy, the Chinese government has successively established and issued regulations, policies and plans on geothermal energy, providing policy and regulation support for geothermal energy utilization.

Therefore, the applications of HGSHP systems have been growing rapidly since the beginning of the 21st century with financial incentives and supportive government policies. China Renewable Energy Law came into effect on January 1, 2006. The state encourages the application of solar energy and geothermal energy in the new buildings and the retrofit buildings. The “Building Energy Saving Management Regulations” was issued in 2004. National Development and Reform Commission also issued the documentation “National Energy efficiency, mid–long term planning” to push the application of renewable energy in buildings. In August 2006, the State Council promulgated “Strengthening the energy efficiency work” and “China National program to Climate Change” to develop widely renewable energy and especially to support the development and application of wind energy, solar energy, geothermal energy, ocean energy, etc. and spread the technology of space heating and hot water supplying with geothermal energy [59].

In recent years, the Ministry of Construction and the Ministry of Finance jointly also issued much more documents, “Opinions on Promoting Application of Renewable Energy in Buildings”, “Interim Measures for Management of Special Fund for Applications of Renewable Energy in Buildings” and “The Assessment Method of the Renewable Energy Demonstration Projects”, which clearly support the promotion of the utilization of renewable energy in buildings. Excitedly, there are eight key areas in a plan of “Opinions on Promoting Application of Renewable Energy in Buildings”, four of which deal with GSHP.

The municipal governments in China have provided financial support to the development of GSHP and HGSHP. Interim Measures of Chongqing for Management of Special Allowance for Application Demonstration Projects of Renewable Energy Buildings issued by Chongqing in 2006 propose to provide allowance of 800–900 yuan/kW for systems used for renewable energy buildings; Ningbo has implemented the Interim Measures of Ningbo for Usage Management of Special Fund for Energy Conservation and Clean Production, according to which an allowance equivalent to 20% of the actual investment will be provided to the project. Besides, other municipal governments have provided financial support to GSHP, such as Beijing, and Shenyang.

In order to achieve energy conservation, help alleviate global warming and improve local environmental sustainability, the Hong Kong government has paid great efforts on promoting energy efficiency in buildings. In 2006, the government launched the “Action Blue Sky” campaign to mobilize the community to take proper action at personal level to help improve environmental quality, including adopting energy saving measures. To further improve energy efficiency in buildings, a proposal to introduce mandatory implementation of the Building Energy Codes (BECs) for certain new and existing buildings was put forward for public consultation in December 2007. These government efforts have resulted in a comprehensive set of energy efficient schemes, and codes of practice developed and issued to control the total energy consumption in buildings and help raise the public awareness on the importance of energy saving in buildings [60].

The importances of HGSHP and HES are recognized in many countries due to energy saving, high efficiency and environmentally friendly features. In order to facilitate HGSHP development in China, many research organizations and administration departments have organized a series of activities, meeting, training, and exhibitions for the promotional purposes. Many municipal governments enacted local actions, measures, and made a blueprint of development.

4.3. Typical incentive districts

4.3.1. Beijing

Beijing, capital of China, has been promoting the application of new and high technologies for energy supply consumption. In just over a decade, as the Beijing municipal government looks toward achieving sustainable development goals, especially in light of the 2008 green Olympics, energy consumption policy is an important factor in promoting the use of GSHP and HGSHP technology. In 2006, Beijing Municipal Commission of Development and Reform published “Guidance on the Development of Heat Pump in Beijing” to encourage the development of heat pump involving GWHP, GCHP and wasted heat source HP. The policy subsidizes 35 yuan/m^2 to GWHP project and 50 yuan/m^2 to GCHP project. The 12th Five-Year (2010–2015) New Energy and Renewable Energy Development Plan of Beijing Municipal Commission of Development and Reform of GSHP is to reach an accumulative total 50 million m^2 in 2015, and expand area 25 million m^2 [61]. Figs. 5 and 6 respectively show the status and development of GSHP projects and the renewable energy development and utilization plan in Beijing.

The 2008 Beijing Olympic projects exerted 34 renewable energy resources items for the Olympic Village and venues, and nine projects utilize GSHP system. With a building area of 258,000 m^2, the new National Stadium has a seating capacity of 91,000 people for the Olympics [62]. It takes full advantage of the GSHP and ice storage system to provide 14–533 kW cooling load in summer for internal VIP rooms, conference rooms and other functional areas in the stadium. The GSHP and ice storage system separately undertake 70% and 30% loads, respectively. Beijing Olympic Village is the living place for athletes and accompanying officials of countries all over the world. The project is located in the northwest corner of Beijing Olympic Park, with a total building area of 524,400 m^2, of which 150,000 m^2 is for demonstration of the sewage source heat pump technology. This project utilizes sewage source heat pump system for cooling in summer and

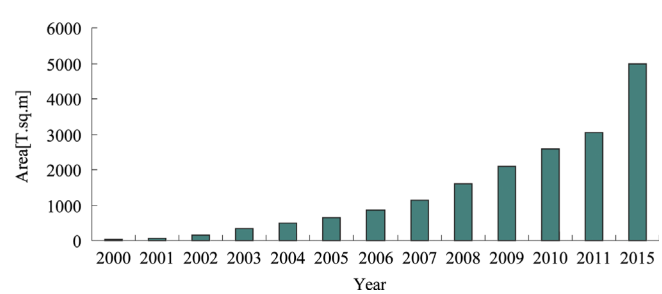

Fig. 5. The trend of GSHP projects in Beijing.

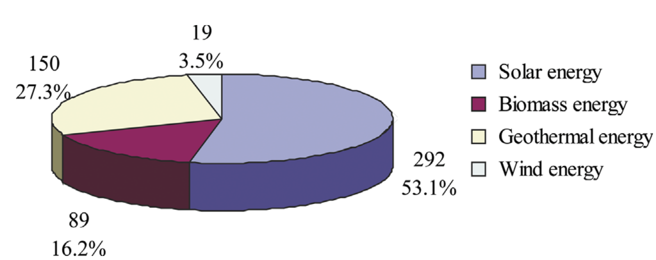

Fig. 6. The renewable energy development and utilization plan in Beijing by 2015 (million TCE).

heating in winter for the Olympic Village, realizing diversified energy utilization. It is actually measured that the project substitutes 1257 TCE conventional energy resources, reducing 3105 t of CO_2 emission and saving 1.25 million RMB of operation cost.

4.3.2. Shenyang

Shenyang, capital of Liaoning Province in the northeast of China, is the fastest one facilitating the utilization of HGSHP in recent 10 years. The Shenyang municipal government has promised to implement preferential taxation and services policies to its districts for the expansion of application. These years a total of 78.8 billion RMB has been invested into the implementation of over 460 key projects to reverse the city's environmental situation [6]. Fig. 7 shows the investment in HGSHP and GSHP projects in Shenyang. In October 2006, Shenyang government issued the acceleration documentation, "Implementation work guidance on boosting the construction and application of GSHP". The heat pump will become the predominant heat supply pattern in Shenyang city in order to reform the traditional heat supply pattern and popularize hybrid energy technology to partly substitute for coal-firing heating. In Shenyang, GWHP, HGSHP and renewable water HP systems are distributed mostly in the core region of city whereas GCHP and sewage source heat pump systems are only applied in individual projects. Fig. 8 shows the status of GSHP projects in Shenyang.

The statistics [63] shows the areas of GSHP projects in Shenyang; and GWHP projects account for about 64.9%, renewable water HP projects account for about 18.1%, HGSHP projects account for about 16.6%, GCHP projects account for about 0.4%, as shown in Fig. 9. Actually, the future growing potential of a large scale of HGSHP is promising.

4.4. Heating/cooling load imbalance and economic necessity

Due to its huge area, China is divided into five climate zones from north to south in the thermal design and engineering, involving severe cold, cold, hot summer and cold winter, temperate, hot summer and warm winter [64]. In north areas, the main

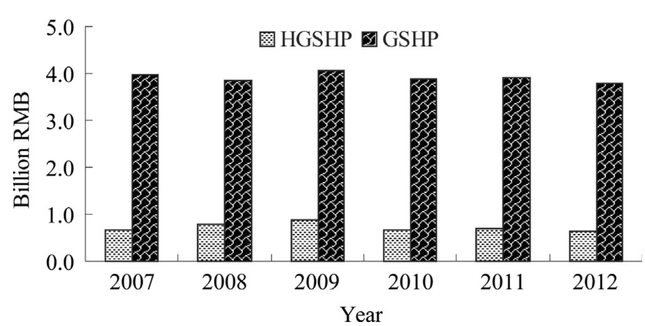

Fig. 7. The investment in HGSHP and GSHP projects in Shenyang.

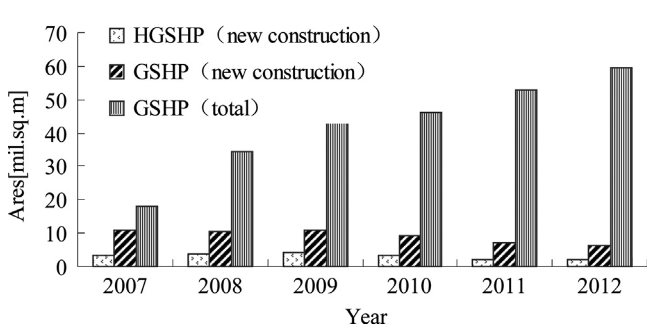

Fig. 8. The status of GSHP projects in Shenyang.

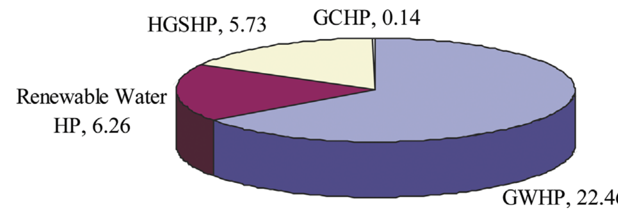

Fig. 9. The areas of GSHP projects in Shenyang (million m^2).

attention is heating, while in south, cooling. An absolutely large part of China is in need of both heating and cooling. The standard for climate region for building and civil engineering indicate the big imbalance between heating and cooling load in the hot summer and cold winter (HSCW) regions [65].

The coexistence of various kinds of GSHP is caused by the multiple climate zones in China. Extreme climate makes the cooling and heating load imbalanced, but the climate and the imbalance of cooling and heating load have become a dominant reason of promotion of auxiliary heat rejecters (or supplemental heat sources) in using GSHP systems. In China, hot summer and cold winter zone covers 16 provinces and autonomous regions with 550 million of population [66].

If the heat extracted from the ground annually is not equal to the heat rejected to it, the balance of geothermal energy will be difficult to be kept and the GSHP system cannot run steadily; thus the cumulating energy-body earth cannot satisfy the energy demand for a long time. How to treat the energy balance between summer and winter and make operation reasonable is very important and critical.

Although there is a ground temperature recovery in transient seasons, the imbalance cannot be ignored. After long time running with a great deal of net heat reject/extract into/from the ground, the initial ground temperature field will change and energy equilibrium will be destroyed. Therefore, it is necessary to exploit the energy supplement system or HES. The energy supplement means the positive energy storage and reaches an annual balance of the energy source. The HES plan combining many types of energy sources, such as geothermal energy, solar energy, waste energy and seasonal nature energy. HES can also meet the need of peak load of a short term.

In addition, there is also a powerful economic reason to promote using of HGSHP in China. For example, Xi'an "Gate of the city" project, total investment cost 26 million RMB, equivalent 257 yuan/m^2. Of this total, increased cost is 13.7 million RMB and equivalent 135 yuan/m^2 by the hybrid system. The simple payback is calculated as the increased first cost of the HGSHP system divided by the annual energy and maintenance cost savings. The project static investment payback period is 5.9 years [67]. The costs and benefits of actual HGSHP systems in all of these climates may be quite different because of the particulars of the application, operating frequency, environment parameters, geological conditions, and the cost of labor in the local economy.

It is clear that HGSHP systems can be economically feasible in some locations where GSHP systems may not. Therefore, in locations with more balanced heating and cooling loads, hybrid systems offer smaller advantages and may have even longer paybacks.

4.5. Prophase basic work of HGSHP

HGSHP systems are being installed more frequently for space heating and cooling and hot water in some European countries because of the rich technology and experience. Although some GSHP systems were installed in China, the application of HGSHP systems

proceeds with comparative slowness in China. Fortunately, at present more and more science and technology organizations have begun to pay more attention to the supply energy source, thermal (cold) energy storage and HGSHP system. Some domestic universities and organizations have been addressing the R&D work of principle, technology characteristic and research state of HGSHP. Its control strategies, design procedure and optimization design are analyzed in detail and some development suggestions are brought forward [68,69].

In the literatures [70–73], a new system, called the integrated soil cold storage and ground source heat pump (ISCS and GSHP) system, was presented. The ISCS and GSHP system is operated under the following three conditions: (a) storing cold energy into soil (charging) during off-peak period at night in summer; (b) providing air-conditioning by releasing the cold energy stored in soil (discharging) at daytime, where thawing and freezing take place periodically in the soil during summer air-conditioning period; and (c) supplying heat to buildings in winter. The ISCS and GSHP system is basically applicable to the cooling-dominated buildings. Besides, the operation performance of the ISCS&GSHP system used for a demonstration building is studied.

The theoretical and experimental studies, performed by some Chinese researchers [74,75], promote the design and application of the SAGSHP systems. In the paper [76], Hebei University of Technology scholars analyze the performance of underground thermal storage in a SAGSHP system for a residential building. Based on the experimental results in the climate case of Tianjin, the performance during a longer period was simulated by the unit modeling. The results show that the performance of underground thermal storage of SAGSHP depends strongly on the intensity of solar radiation and the matching between the water tank volume and the area of solar collectors. For the case of Tianjin, the efficiency of underground thermal storage based on the total solar radiation and absorbed solar energy by the collectors can reach over 40% and 70%, respectively. It is suggested that the ratio of the tank volume to the area of solar collectors should be in the appropriate range.

In addition, Chongqing University has investigated the control strategies, design procedures and optimization designs of different kinds of HGSHP systems and provided general methodologies and advices for optimal design and operation of such HGSHP systems [77]. Huazhong University of Science and Technology scholars developed artificial neural network (ANN) models for predicting the ExFT of the ground heat exchanger. A numerical simulation package of a CTGSHP system is adopted for training and testing the model. Results show that the ANN model can predict the ExFT of the ground heat exchanger with an absolute error less than 0.2 °C [78].

In 1999, Jilin University of China started investigating the geothermal energy for GSHP [79–82], and its researchers have been engaged in GSHP and HES for decades. From 2005, on the basis of previous researching works they proposed HES (e.g., solar energy, underground thermal energy storage, waste heat), and began to study the correlative basic theoretic problems in the field of GSHP with HES [83,84]. By analyzing the heat transfer process of these systems, researchers established the mathematical models for the composing units, and used software analysis tools for many factors' systemic analysis and research. They set up demonstration projects and took some experiments and numerical simulation analysis in the international cooperation with new energy and industrial technology development organization (NEDO) of Japan, Oklahoma State University of U.S., Nottingham university of UK, etc. [85–87].

However, the technology of HES with HGSHP is in the stage of theoretical and experimental exploration and has many unsolved problems in theory and practice, so more work needs to be done in China.

5. Typical trial of HGSHP in China and other countries

5.1. Function of supporting energy supplement

The HGSHP systems utilize auxiliary energy source to balance the annual heat rejection to the ground and the annual heat extraction from it. With the supplemental heat source or sink, the size of the ground loop heat exchanger may be reduced significantly. For many hybrid system engineering projects, a closed-circuit cooling tower is chosen as the secondary heat rejection device and a gas-fired boiler is chosen for the secondary heat supply device. The cooling tower is assumed to be located upstream of the ground heat exchanger in cooling dominated locations and the boiler is assumed to be located downstream of the ground heat exchanger in heating dominated applications. It is of great importance to make HES widely used around world, especially in developing countries because of their environmental and economic benefits.

For HGSHP systems, the first cost of supplemental heat rejecters and increased operating costs due to additional fan and circulation pump energy consumption are expected to be small compared to the savings in drilling costs and heat pump operating costs for cooling dominated buildings.

Based on the hourly simulation results [34], the optimal HGSHP system for the sample cooling dominated building (the ratio of its annual cooling load to heating load is 1.59) can save 35% initial cost and 20.79% operating cost in first year operation compared with the common GSHP system. Because the performance of GSHP system degrades year by year, the economical benefit of the HGSHP system is more obvious in long term operation. The optimal HGSHP system can save 44.69% operating cost and 40.05% total cost compared with the common GSHP system in 10 years operation.

Analysis of the United States Department of Defense (DoD) data shows that GSHP projects have been the most cost effective in the South, Southeast, Midwest, and Mid-Atlantic regions [88]. The DoD report on the use of GSHP concludes that the economic value of hybrid systems is most apparent in warm and hot climates where cooling loads are the highest. Although hybrid systems with heat recovery options are deemed somewhat attractive for regions of moderate climate, no economic value could be justified for cold climates even with heat recovery.

5.2. Function of hybrid types and control modes

In the recent research, it is found that numerous efforts have focused on the means of HGSHP operation mode control for seeking a better efficiency. America's Oklahoma State University Jeffrey D. Spitler et al. presented a study of various control strategies of a GSHP system with a cooling tower as the supplemental heat rejecter [33]. A 1320 m^2 office building was chosen as the example building for the comparative study. Three typical operational modes on cooling towers refer to set point, temperature difference, and preset schedule control.

For a HGSHP system, a set point temperature control strategy is often used to operate the cooling tower. The cooling tower is activated when the EFT of the heat pump or ExFT exceeds an upper limit temperature. Another control strategy might be called a temperature difference control strategy. When the temperature difference between the EFT or ExFT of the heat pump and the ambient wet-bulb temperature (open circuit cooling tower) or the ambient dry-bulb temperature (closed circuit fluid cooler) exceeds a set value, the supplemental heat rejecter is activated. A third type of control strategy, might be called a “preset schedule control”. To avoid a long-term temperature rise, the supplemental heat rejecters are set to run for 6 h during the night to store cold energy in the ground.

All of the control strategies face the challenge of how to choose a proper set point value or preset schedule to get the minimum system operating cost. Although many control strategies of HGSHP system have been investigated, the current available control strategies might be far from optimal. Therefore, more sophisticated control strategies which are able to optimally control the HGSHP system are highly desirable.

5.3. Numerical simulation and practical experiment

Up to now, the idea of HES (e.g., seasonal underground thermal energy storage in an0 SAGSHP system) has been widely accepted under the driving force of the rapidly increasing applications of GSHP. It has been recognized as being among the cleanest, most energy-efficient and cost-effective systems for space heating and cooling, and other heat engineering. So some practical experiments will be put into action gradually for promoting application of HGSHP system.

For instance, the performance characteristics of a ground source heat pump greenhouse heating system with a 246 m horizontal 12.7 mm nominal diameter closed-loop ground heat exchanger and the use of phase change materials (PCM) for energy saving and management in greenhouses with 30 m^2 were investigated in Turkey. The COP of the heat pump and the system were obtained, to be in the range of 2.3–3.8 and 2–3.5 respectively [89].

The literature [90] described a detailed practical experiment of SAGSHP system with solar seasonal thermal storage installed in a detached house in Harbin, China. The solar seasonal thermal storage was conducted throughout the non-heating seasons. In summer, the ground was used as the heat sink to cool the building directly. In winter, the solar energy was used as a priority, and the building was heated by a GCHP and solar collectors alternately. The results show that the system can meet the heating–cooling energy needs of the building. In the heating mode, the heat directly supplied by solar collectors accounted for 49.7% of the total heating output, and the average COP of the heat pump and the system were 4.29 and 6.55, respectively. After a year of operation, the heat extracted from the soil by the heat pump accounted for 75.5% of the heat stored by solar seasonal thermal storage.

Although there is limited potential of using GSHP due to the high density of high-rise buildings in Hong Kong, the use of the GSHP in buildings for energy efficiency was investigated and analyzed in several studies. The simulation of a HGSHP with domestic hot water (DHW) heating systems using HVACSIM+ was presented by Cui et al. [91]. The results showed that this HGSHP system can effectively alleviate the imbalanced loads of the ground heat exchanger and can offer almost 95% DHW demand.

From 2005, Jilin University of China started to investigate the energy storage and complement in HES based on heat pump [92–94]. The researchers engaged in a hybrid heat pump system which include solar collector, GFX, hot water storage tank for the recovery of low-grade energy of sewage. Fig. 10 illustrates a schematic of the solar assisted sewage source heat pump system. The system uses the solar energy and the sewage as the low temperature heat sources. The sewage not only can preheat the cold water entering the evaporator (the low temperature end), but also can preheat the cold water entering the condenser (the high temperature end), so the system can be selected for optimization of the design parameters, component configuration and control strategies to promote system efficiency, reduce the life cycle cost of the system and balance the loads.

Therefore, the researching work aims to establish a GFX module, a solar collector module, a heat pump module and a hot water storage tank module, etc. Details are as follows. In the example system there are two GFXs, GFX 1 and GFX 2. Where G_1 is flow rate of GFX 1, G is the total flow rate of GFX 1 and GFX 2, and F is the water distribution ratio ($F = G_1/G$). The typical operational modes on the load of sewage heat resource, such as preheating the low temperature end ($F=1$), preheating the high temperature end ($F=0$) and both ($0<F<1$) were studied. The analysis results are as follows:

1. $F=0.5$. It is found that the optimum area of solar collector is 40–60 m^2 by analyzing outlet temperature of fluid in condenser and supply electric power. With the increase of area of solar collector, the COP of heat pump and system both increase.
2. $F=0$. Because the low temperature end is heated by electricity, the outlet temperature of fluid in condenser is increased, and the COP of system is very low.
3. $F=1$. The supply electric power of low temperature end decreases and COP of system increases, but the outlet temperature of fluid in condenser is only 36 °C. Compared with the others systems, the hot water temperature decreases remarkably, so it has narrow application scope.
4. $F=0$, 0.2, 0.35, 0.5, 0.6, 0.8, 1.0. Comparing the outlet temperature of fluid in condenser and supply electric power, it is found that $F=0.5$ is a critical point. Fig. 11 shows the relationship between water distributed ratio, outlet temperature of fluid in condenser and supply electric power (solar collector area $S=50$ m^2). If $F>0.5$, the outlet temperature of fluid in condenser decreasing trend increases and the supply electric power decreasing trend decreases. So $F=0.5$ is the optimum point for decreasing the supply electric power and obtaining higher outlet temperature of fluid in the condenser.

6. Further task and proposal of HGSHP R&D

As we reviewed the successful HGSHP R&D in some countries of the world, the strategy plan will be proposed to China, which serves as the basic research work and the theoretical understanding for the first step, and the plan can guide the future and

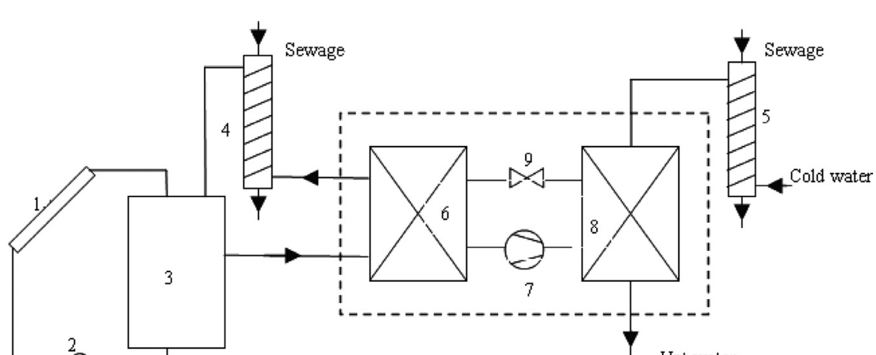

Fig. 10. Schematic diagram of the solar assisted sewage source heat pump system: (1) solar collector, (2) circulation pump, (3) hot water storage tank, (4) GFX1, (5) GFX2, (6) evaporator, (7) compressor, (8) condenser, and (9) expansion.

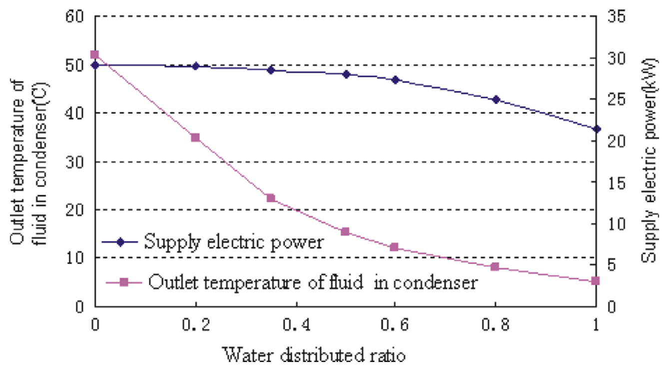

Fig. 11. The relationship between water distributed ratio, outlet temperature of fluid in condenser and supply electric power (solar collector area $S=50$ m^2).

facilitate research, development, implementation and integration of HES technologies that optimize energy utilization by improving overall energy efficiency and economic growth in heating and cooling of the building, while benefiting the local and global environment.

As fundamental research problems, proposals for consultation are provided here for further application and development of HGSHP. They mainly contain the following:

1. Optimization of the design procedure and control strategy. HGSHP systems have many degrees of freedom; there are trade-offs between the reduction in size of the ground loop heat exchanger, the size of supplemental heat rejecters, and the control strategy. Development of an optimal design procedure could simultaneously optimize all of the parameters of interest.
2. Researching on system configurations and the interaction of different components in order to increase the performance and minimizing the life-cycle cost. Influence of operation cost on time-of-day electricity rates, and diverting the extra energy storage for an independent DHW system should be studied.
3. Further research on the fundamental theory of components models to improve the calculation precision. A variety of components models have resulted in difficulties to evaluate and compare different system designs. Therefore, efforts are in progress to develop suits for these models which would allow for direct comparison of results. New experimental systems should be designed to resemble existing simulation models to allow for simple comparison of results. Additionally, these models need to be incorporated into full system simulators.
4. The application of HGSHP systems should be based on different location and climatic zones in China. Considering the practical application, numerous efforts will be made to explore the impact of cycle and time quota of HES and seek an optimal actual effect in the HGSHP systems.
5. Furthermore, the development and evolution of heat flow field from more pumping/injecting wells in GWHP for long term running is explored to define the role of the space in heat flow field and to avoid inter-regional interference and thermal penetration/breakthrough between wells or between well groups or between areas by using HES.
6. As known, without HES an exclusive GSHP requires the longer operational time and leads to overload resulting in underground structure variation that usually weakens its thermal ability and leads to the in the long-term application, such as thermal strain and distortion in the underground structure. Therefore, the failure of ground heat exchangers under the hot-wet migration, energy flow, and variable dynamic load needs to be researched
7. The research work mainly relies on the model analysis and computational simulation, and also will be based on the experiment investigation and validation, from the practical preliminary experiments, and small engineering projects to the large-scale projects.

Based on the primary studies and investigations, some practical projects will be demonstrated gradually. Through the practice, the utilization of HES will be improved and promoted. It a feasible technology will be implemented for a variety of energy systems, from residential to commercial and from industrial to agricultural. By contributing to large-scale energy efficiencies, HGSHP system significantly reduces environmental impacts caused by energy activities, increases the potential uptake of some renewable energy technologies, increases the potential for sustainable energy development and subsequently leads to better energy security.

The investigation of these problems will help strengthen theoretical understanding, facilitate the progress of HES and improve extensive application of HGSHP in China and other countries.

7. Conclusion

HES are strategic and necessary measures for the efficient utilization of renewable resources and sustainable energy. It is valuable to solve the problem of the imbalance between cooling load and heating load in some extreme hot or cold climate areas, especially in the north and south of China. This imbalance in heat rejection/extraction can cause heat buildup in the ground to the point where heat pump performance is adversely affected and hence efficiency of system and possibly occupant comfort are hampered.

As we know, the most aspects of HES are companioning with the progress of GSHP in the field of using geothermal energy, so these will also promote HGSHP technology. Especially, we should make more effect to the progress of HGSHP with renewable energy. Further, the HES may involve complicated unsteady processes that include energy rejection, accumulation, preservation and extraction. Therefore the basic issues were emphasized including the investigation of system design parameters, component configuration and control strategies of the HES. Anyway, the investigation of these problems will strengthen theoretical and practical understanding and facilitate more extensive application of HGSHP in the world.

Acknowledgments

The authors gratefully acknowledge the financial support from the NSFC (National Natural Science Foundation of China) under the Grant nos. 51076059, and 41072198, the Key Laboratory of Songliao Aquatic Environment of Ministry of Education, the Doctor Scientific Research Staring Foundation of Jilin Jianzhu University, and the Department of Education of Jilin Province.

References

[1] Gentry Jason E, Spitler Jeffrey D, Fisher Daniel E, Xu Xiaowei. Simulation of hybrid ground source heat pump systems and experimental validation. In: Proceedings of the 7th international conference on system simulation in buildings; 2006.
[2] Allen A, Burgess J. Developments of geothermal utilisation in the Irish Republic. In: Proceedings of the 2010 world geothermal congress, Bali, Indonesia; April 25–29, 2010, Paper no. 0157, 9 pp.
[3] Lund John W., Freeston Derek H., Boyd Tonya L. Direct utilization of geothermal energy 2010 worldwide review. In: Proceedings of the world geothermal congress 2010, Bali, Indonesia; 2010.
[4] International Geothermal Association. Renewables 2013 global status report; 2013.
[5] Small-scale renewables: big problem, small solution. In REW Guide to North American Renewable Energy Companies 2013, supplement to Renewable Energy World Magazine; March–April 2013. p. 18–24.

[6] Gao Qing, Li Ming, Yu Ming, Spitler Jeffrey D, Yan YY. Review of development from GSHP to UTES in China and other countries. Renewable and Sustainable Energy Reviews 2009;13:1383–94.
[7] China's energy policy 2012. Information Office of the State Council. the People's Republic of China. October 2012, Beijing. 1st ed.; 2012.
[8] Glance-China Five-Year Plan for Renewable. China National Energy Administration and China National Renewable Energy Centre; 2012.
[9] Kavanaugh SP, Rafferty K. Ground-source heat pumps: design of geothermal systems for commercial and institutional buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc; 1997.
[10] Xu Xiaowei. Simulation and optimal control of hybrid ground source heat pump systems. Oklahoma, USA: Oklahoma State University; 2007 ([Ph.D. dissertation]).
[11] Chen Chang. Dynamic modeling and control of hgshp systems. Quebec, Canada: Concordia University, Montreal; 2008 ([Master dissertation]).
[12] International Geothermal Association. Renewables global futures report 2013; 2013.
[13] Ozgener Onder, Hepbasli Arif. A review on the energy and exergy analysis of solar assisted heat pump systems. Renewable and Sustainable Energy Reviews 2007;11:482–96.
[14] Huang BJ, Chyng JP. Performance characteristics of integral type solar assisted heat pump. Solar Energy 2001;71(6):403–14.
[15] Chyng JP, Lee CP, Huang BJ. Performance analysis of a solar-assisted heat pump water heater. Solar Energy 2003;74:33–44.
[16] Badescu V. Model of a thermal energy storage device integrated into a solar assisted heat pump system for space heating. Energy Conversion and Management 2003;44:1589–604.
[17] Torres Reyes E, Picon Nunez M, Cervantes De G. Exergy analysis and optimization of a solar-assisted heat pump. Energy 1998;23(4):337–44.
[18] Cervantes GJ, Torres-Reyes E. Experiments on a solar-assisted heat pump and an exergy analysis of the system. Applied Thermal Engineering 2002;22: 1289–97.
[19] Bi Y. Study on the heating of solar-ground source heat-pump. China: Tianjin University; 1995 ([Master dissertation]).
[20] Bi Yuehong, Guo Tingwei, Zhang Liang, Chen Lingen. Solar and ground source heat-pump system. Applied Energy 2004;78:231–45.
[21] Shahed Ayon M, Harrison Stephen J. Preliminary review of geothermal solar assisted heat pumps. In: Proceedings of the 4th Annual Canadian Solar Buildings Conference, Toronto, 2009.
[22] Rad Farzin M, Fung Alan S, Leong Wey H. Combined solar thermal and ground source heat pump system. In: Proceedings of the 11th international IBPSA conference, Glasgow, Scotland; 2009.
[23] Chiasson AD, Yavuzturk C. Design of school building HVAC retrofit with hybrid geothermal heat-pump system. Journal of Architectural Engineering©Asce 2004:103–11.
[24] Chiasson AD, Yavuzturk C. Assessment of the viability of hybrid geothermal heat pump systems with solar thermal collectors. ASHRAE Transactions 109 (2), 2003:487–500.
[25] Rad Farzin M, Fung Alan S, Leong Wey H. Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada. Energy and Buildings 2013;61:224–32.
[26] Ma ZL, Yao Y. Application prospects of sewage source water heat pump system. China Water & Wastewater 2003;19(7):41–3.
[27] Baek, N.C. Study on the heat pump system using waste water as a heat source. Energy Research and Development 16,1994:56–63.
[28] Baek NC, Shin UC, Yoon JH. A study on the design and analysis of a heat pump heating system using wastewater as a heat source. Solar Energy 2005;78: 427–40.
[29] Tomlinson JJ. Heat recovery from wastewater using a gravity-film heat exchanger. Federal Energy Management Program. Energy Division, Oak Ridge National Laboratory, 2005.
[30] Tomlinson JJ. GFX evaluation letter. Buildings Technology Center Energy Division. Available from: ⟨www.eren.doe.gov/buildings/emergingtech⟩, 2000.
[31] Unique ground-source heat pump system at real-estate office. IEA. OECD. CA 99.540/3B.R01. Available from: ⟨http://www.nrcan.gc.ca⟩.
[32] Shawn Alex Hern. Design of an experimental facility for hybrid ground source heat pump systems. Stillwater, Oklahoma: Oklahoma State University; 2004 ([Master dissertation]).
[33] Yavuzturk C, Spitler JD. Comparative study of operating and control strategies for hybrid ground-source heat pump systems using a short time step simulation model. ASHRAE Transactions 2000;106(2):192–209.
[34] Man Y, Yang HX, Fang ZH. Study on hybrid ground-coupled heat pump systems. Energy and Buildings 2008;40(11):2028–36.
[35] Man Y, Yang HX, Wang JG. Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong. Applied Energy 2010;87:2826–33.
[36] Park Honghee, Lee Joo Seoung, Kim Wonuk, Kim Yongchan. Performance optimization of a hybrid ground source heat pump with the parallel configuration of a ground heat exchanger and a supplemental heat rejecter in the cooling mode. International Journal of Refrigeration 2012;35(6):1537–46.
[37] Park Honghee, Lee Joo Seoung, Kim Wonuk, Kim Yongchan. The cooling seasonal performance factor of a hybrid ground-source heat pump with parallel and serial configurations. Applied Energy 2013;102:877–84.
[38] Sayyadi Hoseyn, Nejatolahi Mostafa. Thermodynamic and thermoeconomic optimization of a cooling tower-assisted ground source heat pump. Geothermics 2011;40:221–32.
[39] Pardo N, Montero Á, Martos J, Urchueguía JF. Optimization of hybrid- ground coupled and air source-heat pump systems in combination with thermal storage. Applied Thermal Engineering 2010;30:1073–7.
[40] Nam Yujin, Ooka Ryozo, Shiba Yoshiro. Development of dual-source hybrid heat pump system using groundwater and air. Energy and Buildings 2010;42:909–16.
[41] Yang Wei, Zhou Jin, Xu Wei, Zhang Guoqiang. Current status of ground-source heat pumps in China. Energy Policy 2010;38:323–32.
[42] Yang H, Cui P, Fang Z. Vertical-borehole ground-coupled heat pumps: a review of models and systems. Applied Energy 2010;87:16–27.
[43] Federal Energy Management Program. Assessment of hybrid geothermal heat pump systems, technology installation review; December 2001. Available from: ⟨http://www1.eere.energy.gov/femp/pdfs/hyhgp_tir.pdf⟩.
[44] Phetteplace G, Sullivan W. Performance of a hybrid ground-coupled heat pump system. ASHRAE Transactions 1998;104(1b):763–70.
[45] Singh JB, Foster G. Advantages of using the hybrid geothermal option. In: Proceedings of the Second Stockton International geothermal conference, The Richard Stockton College of New Jersey; 1998. ⟨http://styx.geophys.stockton.edu/proceedings/hybri/singh/singh.PDF⟩.
[46] Lundin S-E, Eriksson B, Borrteknik T, Brinck B. Drilling in hard rock and borehole heat exchangers for seasonal stores. In: Proceedings of the 9th international conference on thermal energy storage, vol. 1; 2003. p. 399–404.
[47] Bernier Michel, Shirazi Ali Salim. Solar heat injection into boreholes: a preliminary analysis. In: Proceedings of the 2nd Canadian solar buildings conference, Calgary; June 10–14, 2007.
[48] Trillat-Berdal V, Souyri B, Fraisse G. Experimental study of a ground-coupled heat pump combined with thermal solar collectors. Energy and Buildings 2006;38(12):1477–84.
[49] Ozgener Onder, Hepbasli Arif. Performance analysis of a solar-assisted ground-source heat pump system for greenhouse heating: an experimental study. Building and Environment 2005;40:1040–50.
[50] Benli Hüseyin, Durmuş Aydın. Evaluation of ground-source heat pump combined latent heat storage system performance in greenhouse heating. Energy and Buildings 2009;41:220–8.
[51] Hiasson AD, Spitler JD, Rees SJ, Smith MD. A model for simulating the performance of a pavement heating system as a supplemental heat rejecter with closed-loop ground-source heat pump systems. ASME Journal of Solar Energy Engineering 2000;122(4):183–91.
[52] Khan MH, Varanasi A, Spitler JD, Fisher DE, Delahoussaye RD. Hybrid ground source heat pump system simulation using visual modeling tool for hvacsim+. In: Proceedings of the 8th international IBPSA conference, Eindhoven, Netherlands; August 11–14, 2003.
[53] Ramamoorthy Mahadevan, Jin Hui, Chiasson Andrew D, Spitler Jeffrey D. Optimal sizing of hybrid ground-source heat pump systems that use a cooling pond as a supplemental heat rejecter—a system simulation approach. ASHRAE Transactions 2001, 26–38;107(Part 1).
[54] Hackel Scott, Pertzborn Amanda. Effective design and operation of hybrid ground-source heat pumps: three case studies. Energy and Buildings 2011;43:3497–504.
[55] Alavy Masih, Nguyen Hiep V, Leong Wey H, Dworkin Seth B. A methodology and computerized approach for optimizing hybrid ground source heat pump system design. Renewable Energy 2013;57:404–12.
[56] Ministry of Science and Technology of the PR China. China's geothermal energy utilization; 2012.
[57] State Intellectual Property Office of the P.R.C. ⟨http://www.sipo.gov.cn/⟩, 2013.
[58] Fang Li, Peng Deng. Analysis on the patented technology development in geothermal heat pumps industry. Contamination Control & Air-Conditioning Technology 2009;3:1–4.
[59] Xu W. Survey and analysis of domestic GSHP application. Construction & Design for Project China 2006;12:16–9.
[60] Ma Zhenjun, Wang Shengwei. Building energy research in Hong Kong: a review. Renewable and Sustainable Energy Reviews 2009;13:1870–83.
[61] Beijing Municipal Commission of Development and Reform. The 12th five-year new energy and renewable energy development plan of Beijing; 2011.
[62] Xiling Wang, Guixia Ding. Application of energy-saving technology of ground source heat pump system to the National Stadium. Refrigeration and Air Conditioning 2010;10(5):79–84.
[63] Xin Wei. Analysis on GSHP Application in Shenyang. Public Utilities Design 2009(6):59–63.
[64] National standard of the People's Republic of China. Thermal design code for civil building, GB50173-93, China Plan Press; 1993.
[65] Professional standards of China. Design standard for energy efficiency of residential buildings in hot summer and cold winter zones, JGJ134-2001, China Building Industrial Press; 2001.
[66] Ding LX, Chen JF, Guo H. Advancement prospects of GSHP air conditioning system in HSCW zone of China. In: Proceedings of the 7th international energy agency conference on heat pumping technologies: heat pumps-better by nature, vol. 2; 2002. p.1054–64.
[67] Wei Xu. Report on China ground-source heat pump. 1st ed.. Beijing: China Architecture & Building Press; 2008.
[68] Weibo Yang, Mingheng Shi. Study on hybrid ground source heat pump system. Building Energy & Environment 2006;25(3):20–6.
[69] Weibo Yang, Hua Dong, Jun Hu. Discussion on hybrid ground source heat pump system. Energy Research & Utilization 2003;5:32–5.
[70] Fan R, Jiang YQ, Yao Y, Deng SM, Ma ZL. A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection. Energy 2007;32:2199–209.

[71] Fan R, Jiang YQ, Yao Y, Ma ZL. Theoretical study on the performance of an integrated ground-source heat pump system in a whole year. Energy 2008;33:1671–9.

[72] Yu YS, Ma ZL, Yao Y. Energy analysis of cool storage and discharging process in soil. Acta Energiae Solaris Sinica 2007;27(10):1407–12.

[73] Yu YS, Ma ZL, Li XT. A new integrated system with cooling storage in soil and ground-coupled heat pump. Applied Thermal Engineering 2008;28:1450–62.

[74] Weibo Yang, Hua Dong, Jun Hu. R & D of solar–earth source heat pump system. Energy Technology 2003;24(4):160–2.

[75] Weibo Yang, Mingheng Shi, Zhenqian Chen. Numerical simulation and experimental validation of energy storage characteristics of solar-U-tube soil. Journal of Southeast University (Natural Science Edition) 2008;38(4):651–6.

[76] Wang HJ, Qi CY. Performance study of underground thermal storage in a solar ground coupled heat pump system for residential buildings. Energy and Buildings 2008;40:1278–86.

[77] Jia Y. Study on the system optimization and the operation control strategies for hybrid ground source heat pump systems. Chongqing: Chongqing University; 2011.

[78] Gang W, Wang J. Predictive ANN models of ground heat exchanger for the control of hybrid ground source heat pump systems. Applied Energy 2013. http://dx.doi.org/10.1016/j.apenergy.2012.12.031.

[79] Gao Qing, Yu Ming. Development of heating and cooling equipment with saving energy & environment protection—ground source heat pump system. Natural Science Journal of Jilin University of Technology 2001;31(2):96–101.

[80] Gao Qing, Li Ming, Yu Ming. Experiment and simulation of temperature characteristics of intermittently controlled ground heat exchanges. Renewable Energy 2010;35(6):1169–74.

[81] Gao Qing, Mi Lin, Liu Yan. Effect of solar energy storage and ground heat exchanger on the road hydronic ice-snow melting. Acta Energiae Solaris Sinica 2010;31(7):845–50.

[82] Gao Qing, Li Ming, Yu Ming. Restorative characteristics of ground temperature in the intermittent process about the behavior of earth energy in ground source heat pump. In: Proceedings of the 3rd international symposium on heat transfer and energy conservation, GuangZhou, China, vol. 1; 2004. p. 547–52.

[83] Gao Qing, Li Ming, Yan YY. Operation strategy on heat transfer enhancement in the underground multi-boreholes. Acta Energiae Solaris Sinica 2006;27 (1):83–9.

[84] Gao Qing, Li Ming, Yu Ming, Xuan ZH, Ma CQ, Qiao G. Characteristics of temperature distribution control on ground thermal energy storage. Journal of Thermal Science and Technology 2007;28(4):172–6.

[85] Qi Zishu, Gao Qing, Yu Ming, Liu Yan, Bai Li. The method of forecast and analysis of long-term operation on ground-coupled heat pump system. Journal of Jilin University (Engineering and Technology Edition) 2012;42(4): P877–P881 (7).

[86] Qi Zishu, Gao Qing, Liu Yan, Yan YY, Spitler Jeffrey D. The performance improvements of a ground-coupled heat pump system for both building heating and cooling modes. Advanced Materials Research 2012;354–355: P807–P810.

[87] Qi Zishu, Gao Qing, Liu Yan, Yan YY, Spitler Jeffrey D. Analysis and research on the performance of the ground source heat pump system in different areas of China. Applied Mechanics and Materials 2012;148–149:P1137–40.

[88] Ground-source heat pumps at Department of Defense Facilities. Office of the Deputy Under Secretary of Defense (Installations and Environment); January 2007.

[89] Benli Hüseyin. Energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating. Energy Conversion and Management 2011;52:581–9.

[90] Wang Xiao, Zheng Maoyu, Zhang Wenyong, Zhang Shu, Yang Tao. Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas. Energy and Buildings 2010;42:2104–10.

[91] Cui P, Yang HX, Spitler JD, Fang ZH. Simulation of hybrid ground-coupled heat pump with domestic hot water heating systems using HVACSIM+. Energy and Buildings 2008;40(9):1731–6.

[92] Zhu Bai fa. Effect on energy storage and complement in hybrid energy system based on heat pump. China: Jilin University; 2007 ([Master dissertation]).

[93] Yin Yong lan, Gao Qing, Li Ming, Zhu Bai fa. The operating mode of solar assisted heat pump system. Heating, Ventilation and Air Conditioning 2009;39:347–51.

[94] Qi Zishu. Diversity and efficiency on energy mechanism of heat pump system by using earth energy. China: Jilin University; 2012 (Doctoral dissertation).